PRODUCTION OF MANUFACTURED AGGREGATES FROM COAL COMBUSTION BY-PRODUCTS

M. M. Wu (miltonwu@consolcoal.com; 412-854-6708)
R. A. Winschel (dickwinschel@consolcoal.com; 412-854-6683)
G. J. Hasenfus (greghasenfus@consolcoal.com; 412-854-6785)

CONSOL Inc.
Research & Development
4000 Brownsville Road
Library, PA 15129

ABSTRACT

CONSOL R&D has developed a disk pelletization process to produce manufactured aggregates from the by-products of various technologies used to reduce the sulfur emissions resulting from coal combustion. Aggregates have been produced from the by-products of the fluidized-bed combustion (FBC), spray dryer absorption (SDA), and wet lime and wet limestone flue gas desulfurization (FGD) processes. The aggregates made from FBC by-product meet the AASHTO M-283 specifications for Class A coarse aggregates for use in road construction. The FBC aggregates were used to construct a bituminous surface wearing course pavement in 1995. The aggregates made from SDA by-product meet the ASTM C-331 lightweight aggregate specifications for use in concrete masonry units. The SDA aggregates were used as about 50% of the aggregate to manufacture lightweight concrete blocks at a commercial block plant in 1996. The blocks meet ASTM C-90 specifications for lightweight concrete masonry units. In 1997, aggregates meeting both the AASHTO M-283 Class A road aggregate and ASTM C-331 lightweight aggregate specifications were made from mixtures of wet FGD sludge, fly ash, lime and other components. In 1998, field demonstrations using FGD sludge aggregates in road construction and in lightweight concrete block will be conducted.

INTRODUCTION

The production of manufactured aggregates provides a potentially significant opportunity to utilize coal combustion by-products. Aggregate, traditionally made from natural stone and sand, constitutes about 80% by volume of concrete in structural materials and road construction. The U.S. consumption of natural aggregates is well over one billion tons per year. The replacement of natural aggregates with aggregates manufactured from coal combustion by-products could provide an economical high-volume use and substantially expand markets for combustion by-products. Many other utilization options (e.g., structural fill) are limited by consumption volume, seasonal demands, and problems in handling, transportation, and storage. Very few other utilization options could be used as high-volume alternatives to landfill disposal.

Over the last ten years, CONSOL R&D developed a disk pelletization process to produce manufactured aggregates with coal combustion by-products. This process initially was developed to produce construction aggregates from dry FGD (Coolside, LIMB, and spray dryer) and FBC ashes. In 1996, the efforts were redirected to produce construction aggregates from FGD sludge. The aggregates were made in a three-step process involving mixing, disk pelletization, and curing. The properties of the manufactured aggregates were characterized and compared with specifications for use in road and structural construction. The aggregate product may be used as produced, or some or all of it may be crushed to meet a specific size classification or to produce angular pieces for use in paving. A variety of useful products, such as lightweight aggregates, American Association of State Highway Transportation Officials (AASHTO) Class A road aggregates, and concrete aggregates were produced, depending on the specific feedstock materials and the operation of the pelletization process.

RESULTS AND DISCUSSION

Coolside and LIMB Ash Aggregates

The initial objective for CONSOL's aggregate production work was to reduce the waste management costs and overall process costs of two clean coal technologies: Coolside and LIMB sorbent injection FGD processes. The Coolside and LIMB processes were demonstrated successfully at the Ohio Edison Edgewater Station in Lorain, OH, from 1989 to 1992 as part of the DOE Clean Coal Technology (CCT) program. These two processes produce a dry solid waste that must be managed to ensure environmental compliance and economic feasibility. High-strength manufactured aggregates with low abrasion indices were made from Coolside and LIMB ashes. Both aggregates met the ASTM C-331 specifications for lightweight aggregates for concrete masonry units.[1] However, the poor market penetration of the Coolside and LIMB processes did not justify the further development of aggregate production from Coolside and LIMB ashes.

FBC Ash Aggregates

FBC is a commercial technology that combines steam generation with SO_2 control. FBC ash is generated at a temperature of about 1600 °F during coal combustion. The dry ash consists mainly of calcium sulfate, calcium oxide, and coal ash. The manufactured aggregates produced from the dry FBC ash meet the AASHTO Class A aggregate specifications. Although not required by specification, additional tests were conducted to evaluate the effects of natural weathering and freeze/thaw on aggregate properties. The aggregates degraded when they were fully immersed in water during long-term natural weathering and laboratory freeze/thaw tests. Durability was improved by blending FBC ash with pulverized coal (p.c.) fly ash.[2] Approximately 3000 lb of FBC ash aggregates meeting AASHTO Class A aggregate specifications (Table 1) were produced in a semi-continuous batch operation. The only raw materials were FBC ash, p.c. fly ash, and water. Since the aggregates produced were spherical, 70 wt % was rough crushed to produce angular pieces for improved load bearing. Marshall stability testing indicated that the aggregates could produce an excellent asphalt mix. Results of the Marshall stability tests using various asphalt mix designs are shown in Table 2.

The FBC ash aggregates were used as approximately 50 vol % of the coarse aggregates in a flexible bituminous (FB) asphalt mix. The other components of the asphalt mix included commercial No. 8 crushed limestone and about 6.5% AC-20 asphalt. No fine aggregate was used. A 12' x 35' x 1.5-2" test patch was laid as a surface course on a high-volume truck road in West Mifflin, PA, in April 1995. The test patch was monitored for over a year by visual inspection and by collecting and characterizing core samples on a monthly basis from April 28, 1995 to May 30, 1996. FB mixes are designed to be relatively permeable to water. The heavy truck traffic and the permeability of the paving mix made this a severe test of the aggregate durability.

Visual inspections showed that the pavement surface remained uniformly hard and revealed no degradation of the pavement or the aggregate. The surface became too hard to obtain intact core samples with the existing equipment after December 1995. New coring equipment allowed representative core samples to be collected on May 30, 1996. The core samples were extracted with tetrahydrofuran (THF) to remove the asphalt, then screened to determine the size distribution of the aggregates (Table 3). The near-constant size distribution of the core samples indicates that the aggregates maintained their integrity during use for one year. No fines (-8 mesh) were present in the original aggregate, although 33 wt % to 40 wt % fines existed in the recovered cores. In theory, the fines recovered from the cores could have been due to extraneous material, degradation of either the natural or manufactured aggregates, or they could have been generated during the coring operation. To determine the source of the fines (extraneous material, or degraded FBC ash aggregate or limestone), the 8 x 50 mesh and -50 mesh fractions of the THF-extracted core samples were analyzed. The source of the fines in the recovered core samples were estimated from elemental analyses, as follows. The FBC ash aggregate content was estimated from the sulfur content, assuming that the sulfur is derived entirely from FBC ash aggregates. The $CaCO_3$ content, which represents the limestone, was estimated from the difference between the total Ca in each size fraction and the Ca from the FBC ash aggregates in that fraction. The remaining material not categorized as either FBC ash aggregates or $CaCO_3$ was categorized as extraneous material, which includes impurities in the limestone aggregate, and other stones, sand, and dirt deposited in the test patch by traffic. Table 3 lists the estimated sources of the recovered fines. Elemental analysis indicated that the extraneous matter had an SiO_2 content of ~50%; thus, it probably represents sand and dirt. The ratio of FBC ash aggregate to limestone aggregate in the fine fractions remained nearly constant throughout the test period (Table 3). It is concluded that the fines in the cores arose from extraneous materials and from aggregate breakage during the coring operation. All evidence indicates that the FBC ash aggregates were as durable as the limestone.[3]

Spray Dryer Ash Aggregates

The spray dryer adsorption process is a commercial technology that removes SO_2 from the flue gas downstream of the air preheater at a temperature below 300 °F. The dry ash mainly consists of calcium sulfite, calcium hydroxide, and coal fly ash. The manufactured aggregates produced from spray dryer ash meet the ASTM C 331 lightweight aggregate specifications. Both long-term natural weathering and laboratory freeze/thaw tests indicate that spray dryer ash aggregate has good durability.[2]

In late 1995 and early 1996, two batches (1200 lb and 1700 lb, respectively) of lightweight aggregates were produced from spray dryer FGD by-product. The raw materials consisted of spray dryer ash, lime, and water. The properties of the resulting aggregates are shown in Table 4.

The spray dryer ash aggregates were used to produce two batches of lightweight concrete blocks in a commercial block plant in Ohio. The first batch of aggregates was used to produce solid-core 6" x 8" x 16" blocks in 1995. The concrete block feedstocks included spray dryer ash aggregates, coal-fired furnace bottom ash, portland cement (in the weight ratio 44/44/12), and water. The second batch of aggregates was used to produce 75% solid, two-hollow-core, 6" X 8" X 16" concrete blocks in 1996. The concrete block feedstocks included only spray dryer ash aggregates, coal-fired furnace bottom ash, fine boiler slag, portland cement (in the weight ratio 41/23/23/14) and water. The properties of the blocks are shown in Table 5. Both batches of blocks meet ASTM C-90 specifications in unit weight, water absorption and compressive strength for use in concrete masonry units.

FGD Sludge Aggregates

Although CONSOL's manufactured aggregate development program was technically successful, as applied to FBC ash and spray dryer ash, neither the FBC process nor the spray dryer FGD process is widely deployed in the U.S. By far, the most widely used process for controlling sulfur dioxide emissions from coal-fired boilers in the U.S. is the wet FGD scrubbing (lime and limestone processes). Over 20 MM tons of dry unfixated FGD sludge is produced in the U.S.; yet only 7% is utilized. Therefore, the feasibility of producing manufactured aggregates from wet FGD sludge for use in road and structural construction was evaluated. Three separate projects were initiated in September 1996, with funding from CONSOL, Trumbull Corp., the Ohio Coal Development Office (OCDO) and the Illinois Clean Coal Institute (ICCI). The progress of these three projects (CONSOL/Trumbull, CONSOL/ICCI and CONSOL/OCDO) are summarized below. FGD sludges collected from lime wet FGD units were used in the CONSOL/Trumbull and CONSOL/OCDO projects. FGD sludges collected from limestone wet FGD units were used in the CONSOL/ICCI project. The effects of the mix composition (fly ash/FGD sludge weight ratio, fly ash and lime types, other components, and lime dosage) and operating conditions on aggregate properties were evaluated in each project.

<u>CONSOL/Trumbull Project</u>. A joint project between CONSOL and Trumbull Corp., conducted from October 1996 to April 1997, was successful in producing AASHTO Class A aggregates with lime wet FGD sludge. Aggregates meeting AASHTO M-283 specifications for Class A aggregate were produced from FGD sludge from the Duquesne light Elrama Station, fly ash from the Allegheny

Power Harrison Station, hydrated lime and an additional component. The properties of the manufactured aggregates are compared with AASHTO Class A aggregate specifications in Table 6.

CONSOL/ICCI Project. This project, conducted from September 1996 to August 1997, was successful in producing manufactured aggregates from by-products of the limestone wet FGD process (both forced oxidation and inhibited oxidation units). The Springfield City Water, Light & Power (CWL&P) Dallman Station is equipped with a forced oxidation unit that produces a sulfate by-product (gypsum) that has a solids content of 82 wt %. The Public Service of Indiana (PSI) Gibson Station is equipped with an inhibited oxidation unit that produces sulfite sludge by-product that has a solids content of 58 wt %.

Concrete aggregates were produced from the CWL&P Dallman Station gypsum, using only the gypsum, fly ash, hydrated lime, and water. Fly ash/gypsum weight ratios in the mix ranged from 1.47 in Test ICCI-SU-13 to 0.82 in Test ICCI-SU-14. The aggregates produced from Tests 13 and 14 meet all ASTM specifications (Table 7) for use as concrete aggregate. These specifications were met without using any feed component other than gypsum, fly ash, hydrated lime, and water.

Lightweight aggregates produced from Gibson Station and Dallman Station FGD sludges are compared to the ASTM C331 lightweight aggregate specifications in Table 8. Test Nos. 28 and 29 were conducted with PSI Gibson Station sulfite sludge, fly ash and hydrated lime. Test No. 30 was conducted with CWL&P Dallman Station FGD gypsum, fly ash and hydrated lime. A low-density fly ash was used to reduce aggregate unit weight. Aggregates produced in all three tests meet the ASTM specifications for unit weight, clay lumps, grain size and staining for use as lightweight aggregate. In order to determine some of the ASTM C-331 specification properties, masonry units must be produced from the aggregates. Those properties were not evaluated.

Strong aggregates meeting AASHTO M-283 specifications as Class A road aggregate were produced from PSI Gibson Station FGD sulfite sludge, fly ash, hydrated lime and another component. The properties of aggregates are compared with AASHTO Class A aggregate specifications in Table 9.

CONSOL/OCDO Project. This ongoing project, which began in November 1996, was successful in producing manufactured aggregates from FGD sulfite sludges produced at the Ohio Power (a unit of American Electric Power, AEP) Gavin Station and Cinergy Zimmer Station. Both units are equipped with lime wet FGD units and have solids contents of 42% and 46%, respectively. Bench-scale pelletization testing for this project is nearly completed. Small field trials, each using 4000 to 5000 lb of aggregate, will be conducted in 1998 to demonstrate the uses of the aggregates in highway construction and in the manufacture of lightweight concrete blocks.

Lightweight aggregates produced from the Zimmer Station or Gavin Station sludge, fly ash and hydrated lime are compared to the ASTM lightweight aggregate specifications in Table 10. Test No. 13 was conducted with Zimmer Station FGD sludge. Test No. 15 was conducted with AEP Gavin Station FGD sludge. A low-density fly ash was used to reduce the aggregate unit weight. The aggregates produced in Test Nos. 13 and 15 meet or nearly meet the ASTM specifications for unit weight, clay lumps, grain size and staining for use as lightweight aggregate. The aggregates also have other desirable properties such as high compressive strength and low LA abrasion index.

Strong aggregates meeting AASHTO M-283 specifications as Class A road aggregate were produced from the Gavin Station FGD sludge, fly ash, hydrated lime and another component. The aggregate properties are compared with AASHTO Class A aggregate specifications in Table 11.

These results demonstrate that the CONSOL technology is equally applicable to FGD sludges from lime, forced oxidation limestone, and inhibited oxidation limestone FGD units. High quality aggregates meeting commercial specifications can be manufactured from the by-products of all three wet FGD technologies.

EXPERIMENTAL

Manufactured aggregates were produced in a three-step process consisting of mixing, disk pelletization and curing. For FBC ash, the dry ash was first hydrated by mixing it with water in a Littleford Brothers LM-130 batch mixer. The hydrated ash was pelletized with additional water on a 36" i.d. rotary disk pelletizer. The total water added was about 30 wt % of the ash. The pellets were cured for 24 h at about 180 °F and over 90% relative humidity in a 55 gallon curing vessel. The as-produced pellets were generally spherical in shape, and 80 wt % had diameters greater than 3/8". Most of the pellets with diameters greater than 3/8" were crushed to produce angular shapes desirable for use in asphalt concrete. The +8 mesh crushed pellets were blended (70/30) with the uncrushed pellets to produce a 3000 lb batch (10% 1/2" x 3/8", 77% 3/8" x 4 mesh, 13% 4 x 8 mesh). The pellets were evaluated as road aggregates by a variety of tests, including grain size distribution and American Society for Testing and Materials (ASTM) tests C131 (LA abrasion index), C88-83 (soundness index), and C-29-89 (unit weight).

For spray dryer ash, the dry ash was first mixed with the appropriate amount of water in a Littleford LM-130 batch mixer. The wetted material was pelletized and cured as described above. The pellets were evaluated as lightweight aggregates by a variety tests, including ASTM tests C142 (clay lumps), C641 (staining), C29 (unit weight), C136 (grading) and other as required by specifications.

For FGD sludge, the FGD sludge was first mixed with fly ash and lime (and sometimes water or another component) in a Littleford LM-130 batch mixer. The blended material was pelletized and cured as described above.

ACKNOWLEDGMENT

This work was supported by CONSOL Inc., Trumbull Corp., the Ohio Coal Development Office (Grant Agreement Nos. CDO/D-902-9 and CDO/D-95-2), and the Illinois Clean Coal Institute (Project No. 96-1/3.2A-1).

REFERENCES

1. Wu, M. M.; Winschel, R. A.; Wasson, G. E.; Jageman, T. C. "Properties of Solid Wastes from Edgewater Coolside and LIMB Process Demonstrations", 83rd Annual Meeting of the Air & Waste Management Association, Paper No. 90-40.7, Pittsburgh, PA, 1990.

2. Wu, M. M.; Winschel, R. A.; Wasson, G. E. "Composition Effects on the Durability of Aggregates Made from Coal Combustion Wastes", presented at the 1995 International Ash Utilization Symposium, Lexington, KY, October 1995.

3. Winschel, R. A.; Wu, M. M. "Use of Aggregates Produced from Coal-Fired Fluidized Bed Combustion Residues as a Component in Bituminous Concrete", presented at the Ninth International Conference on Coal Science, Essen, Germany, September 1997.

TABLE 1
COMPARISON OF FBC ASH AGGREGATE PROPERTIES WITH AASHTO CLASS A AGGREGATE SPECIFICATIONS

	FBC Ash Aggregates	Class A Aggregates AASHTO M-283 No. 8 Size
LA abrasion index, wt %	19	40 (max)
soundness index, wt %	11	12 (max)
unit weight, lb/ft^3	75	70 (min)
fractured pieces, wt %	70	varies, depends on State regulation
grain size, wt % passing		
½"	100	100
3/8"	89.5	85 - 100
4 mesh	12.9	10 - 30
8 mesh	0	0 - 10

TABLE 2
MARSHALL STABILITY TEST RESULTS FOR ASPHALT MIXES MADE WITH FBC ASH AGGREGATES

Mix	A	B	C	D	E
Mix Composition					
FBC Ash Aggregates, wt %	7.9	16.7	38.5	38.0	37.5
Mfd. Limestone Sand, wt %	62.5	60.6	56.0	56.0	56.0
No.8 Limestone, wt %	23.6	16.7	0.0	0.0	0.0
Asphalt Cement, wt %	6.0	6.0	5.5	6.0	6.5
Test Results					
Marshall Stability, lb	2250	2325	2875	2305	2275
Flow	11	12	14.5	15	15.3
Bulk Specific Gravity	2.236	2.154	1.934	1.936	1.927
Air Voids, %	7.4	10.7	16.1	15.5	15.4
Voids Mineral Aggregate, %	17.4	19.6	21.8	22.1	22.8

TABLE 3
SIZE DISTRIBUTION OF THE THF-EXTRACTED CORE SAMPLES AND ESTIMATED SOURCE OF FINES

	1995							1996
	6/1	6/27	8/3	9/1	10/2	11/1	12/4	5/30
Size Dist., wt %								
+3/8"cm	4	13	9	11	9	6	12	7
3/8" x 4 mesh	45	36	43	42	42	44	31	36
4 x 8 mesh	17	16	15	13	15	16	17	21
8 x 50 mesh	18	19	15	13	13	14	17	20
-50 mesh	16	17	18	21	21	20	23	16
Source of fines, wt %								
8 x 50 mesh								
FBC ash aggregates	-	35	33	30	36	31	31	31
$CaCO_3$	-	48	50	53	50	51	51	49
Extraneous	-	17	17	17	14	18	18	20
-50 mesh								
FBC ash aggregates	-	33	31	29	33	35	29	27
$CaCO_3$	-	41	40	42	42	38	42	42
Extraneous	-	26	29	29	25	27	29	31

TABLE 4
PROPERTIES OF LIGHTWEIGHT AGGREGATES PRODUCED FROM SPRAY DRYER ASH

	Spray Dryer Ash Aggregates, First batch	**Spray Dryer Ash Aggregates, Second Batch**	**Lightweight Aggregate Specifications ASTM C-331**
grain size	Meets ASTM No. 8 -	- Meets ASTM combined Nos. 8/9	No. 8 (coarse) Nos. 8/9 (combined)
dry unit weight, lb/ft ^{3}	52.6 (No. 8) -	- 55.4 (Nos. 8/9)	No. 8 = 55 (max) Nos. 8/9 = 65 (max)
Clay Lumps, wt %	1.7	1.5	2.0
staining material	negative	negative	negative
specific gravity	1.73	1.78	-
water absorption, wt %	5.8	5.5	-
compressive strength, lb	90	120	-

TABLE 5
CONCRETE BLOCK PROPERTIES

	Batch 1 Blocks	Batch 2 Blocks	ASTM C-90 Specifications for Lightweight Concrete Masonry Units
Unit Weight, lb/ft^3, as is	98.0	99.5	105 (max)
Water Absorption, wt %	12.5	14.4	18 (max)
Net Compressive Strength, psi	2140	1940	1900 (min)
Deformation at Failure, %	1.9	1.9	-

TABLE 6
PROPERTIES OF CLASS A AGGREGATES PRODUCED FROM LIME WET FGD SLUDGE

	Test No. TRU-SU-14	AASHTO M-283 Specs for Class A Aggregate
<u>**Aggregate Properties**</u>		
Unit Weight, lb/ft^3	75	70 (min)
LA abrasion index, wt %	27	40 (max)
Soundness index, wt %	0	12 (max)
Grain size	coarse	coarse
Compressive strength	197±53	----

TABLE 7
PROPERTIES OF CONCRETE AGGREGATES PRODUCED FROM LIMESTONE FORCED OXIDATION FGD GYPSUM

	Test No. ICCI-SU-13	Test No. ICCI-SU-14	ASTM C-33 Specs for Concrete Aggregate
LA Abrasion Index, wt %	45	47	50 (max)
Soundness Index, wt %	3.1	1.3	12 (max)
Grain Size	coarse	coarse	coarse
Clay Lump, wt %	0.85	0.79	2 to 10 (max)
Material finer than 75 µm, %	0	0	1.0 (max)
Coal and Lignite Content, %	0	0	0.5 to 1.5
Compressive Strength, lb	76	62	----
Unit Weight, lb/ft^3	75	75	----

TABLE 8
PROPERTIES OF LIGHTWEIGHT AGGREGATES PRODUCED FROM LIMESTONE WET FGD SLUDGES

	Test No. ICCI-SU-28	Test No. ICCI-SU-29	Test No. ICCI-SU-30	ASTM C-331 Specs for Lightweight Aggregate
Unit Weight, lb/ft ^{3}				
as-is	63	65	62	----
dry	52	55	49	55 (max)
Clay Lumps, wt %	1	1	1.5	2 (max)
Grain Size	coarse	coarse	coarse	coarse
Staining	none	none	none	none
Compressive Strength, lb	71	72	154	----

TABLE 9
PROPERTIES OF CLASS A AGGREGATES PRODUCED FROM INHIBITED OXIDATION LIMESTONE FGD SLUDGE

	Test No. ICCI-SU-23	AASHTO M-283 Specs for Class A Aggregate
LA abrasion index, wt %	26	40 (max)
Soundness index, wt %	10	12 (max)
Grain Size	coarse	coarse
Unit weight, lb/ft^3	78	70 (min)
Compressive Strength, lb	338	----

TABLE 10
PROPERTIES OF LIGHTWEIGHT AGGREGATES PRODUCED FROM LIME WET FGD SLUDGES

	OCDO-SU-13	OCDO-SU-15	ASTM C-331 Specs for Lightweight Aggregate
Unit Weight, lb/ft ^{3}			
as-is	68	65	----
dry	56	52	55 (max)
Clay Lumps, wt %	1	1	2 (max)
Grain Size	coarse	coarse	coarse
Staining	none	none	none
Compressive Strength, lb	150	93	----
LA Abrasion Index, wt %	31	34	----

TABLE 11
PROPERTIES OF CLASS A AGGREGATES PRODUCED FROM LIME WET FGD SLUDGE

	OCDO-SU-23	**AASHTO M-283 Specs for Class A Aggregate**
LA abrasion index, wt %	30	40 (max)
Soundness index, wt %	0	12 (max)
Grain Size	coarse	coarse
Unit weight, lb/ft^3	76	70 (min)
Compressive Strength, lb	232	----